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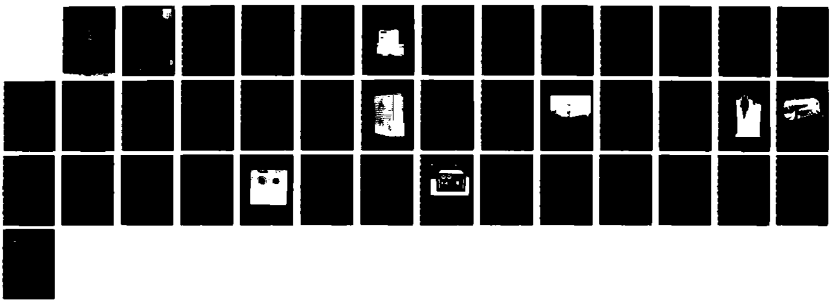

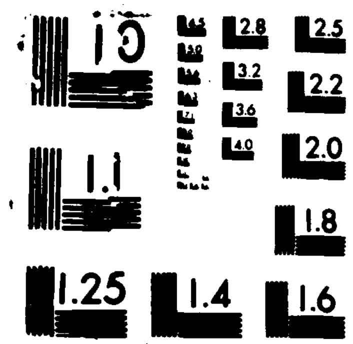

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AFWAL-TR-86-2115

PRE-PROTOTYPE 5 kW FUEL CELL POWER PLANT DEVELOPMENT

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APRIL 1987

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This technical report has been reviewed and is approved for publication.

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JOSEPH P. FELLNER, Project Engineer
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FOR THE COMMANDER

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A five kilowatt Phosphoric Acid Fuel Cell (PAFC) power plant, with the ability to operate on neat methanol, was developed and tested. Overall thermal efficiency at full load (based on the lower heating value of methanol) was 32%. Keywords:

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EXECUTIVE SUMMARY

This report summarizes efforts under a U.S. Air Force Wright Aeronautical Laboratories (Wright-Patterson AFB, OH) sponsored program for the development of a fully automatic 5 kW fuel cell unit for the Air Force for continuous power generation use at remote sites. Methanol, a non-petroleum fuel which is produced from a variety of sources (natural gas, coal, wood and waste materials), has been chosen as fuel for this power source. A preprototype 5 kW fuel cell power plant has been designed, constructed, tested and delivered as a part of this program. A photograph of the power plant is shown in Figure 1.

The design of this power plant is based on the fuel cell power plant technology developed by Energy Research Corporation for the U.S. Army under Contract DAAK70-79-C-0249 (two 3 kW power plants were delivered to the Army Belvoir Research and Development Center in late 1984). It utilizes methanol fuel which is steam reformed to produce hydrogen for the fuel cell stack. The water needed in the steam reformer is recovered from power plant exhaust streams.

The power plant is completely automatic. A microprocessor based controller provides system control during startup, on load operation, and shutdown.

The power plant was tested under various operating conditions for a total of over 500 hours. Fuel consumption was 3.8 lbs/hr at no load (hot idle) and 6.3 lbs/hr at the rated 5 kW, 48 VDC output (6 kW fuel cell stack output). The overall thermal efficiency was 32% based on the regulated output and 34% based on the unregulated fuel cell stack.

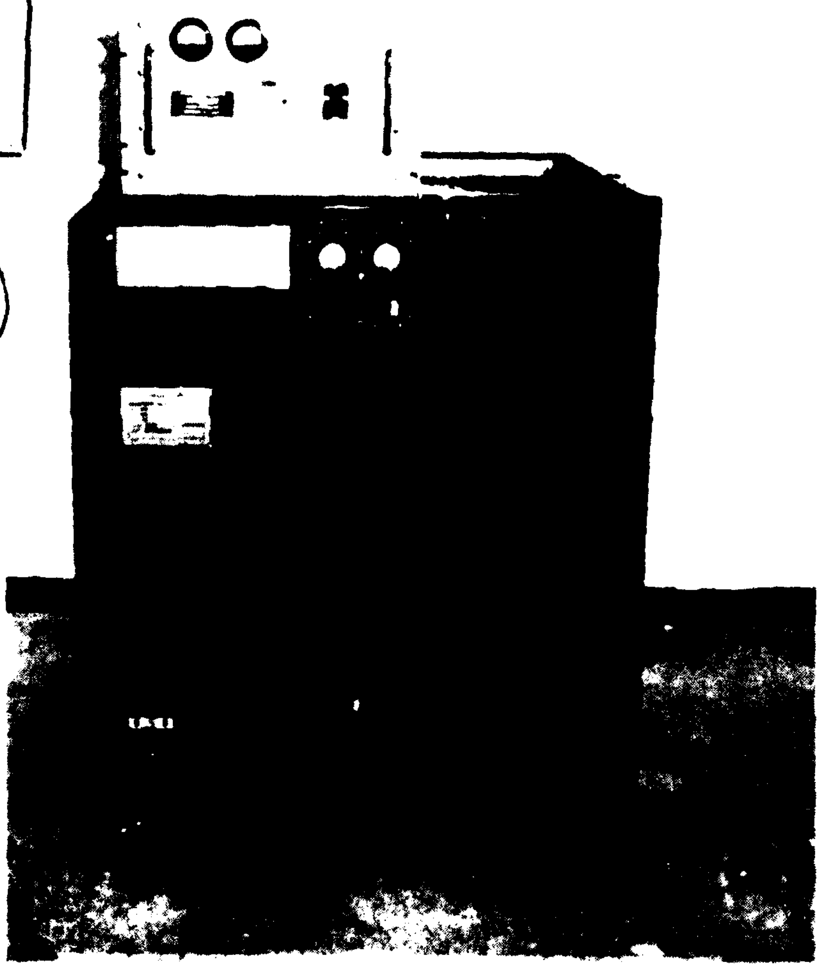

FIGURE 1.
PHOTOGRAPH OF 5 kW POWER PLANT

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1.0 INTRODUCTION

This report presents design and performance data for a 5 kW preprototype fuel cell power plant built for the U.S. Air Force under Contract F33615-82-C-2201. The design of the power plant generally relies on the small fuel cell power plant technology developed by Energy Research Corporation for the U.S. Army Belvoir R&D Center under Contract DAAK70-79-C-0249.

Energy Research Corporation delivered two 3kW prototype fuel cell power plants to the Army in 1984. These plants were designed for mobile applications and used a methanol-water mixture as the fuel.

The main features which distinguish the present Air Force 5 kW power plant from the 3 kW Army units are (1) operation on neat (undiluted) methanol fuel and (2) increased size and weight because of the use of a larger fuel cell stack. These modifications were undertaken to make the power plant more suitable for use at remote, unattended sites where fuel consumption is a major consideration in the choice of a power source.

2.0 DESCRIPTION OF THE POWER PLANT

2.1 DESIGN CONCEPT

The fully automatic methanol fuel cell power plant developed for the U.S. Air Force is based on the use of a methanol-steam reformer with a phosphoric acid fuel cell stack. The power plant system concept is shown in Figure 2.1. Water recovered from the exhaust streams is mixed with neat methanol (supplied externally) onboard the power plant and the solution is fed to the reformer. The reformer generates hydrogen together with by-product carbon dioxide and water vapor.

About two-thirds of the hydrogen react with oxygen in the fuel cell stack to produce electrical energy and water. The unused hydrogen is burned with ambient air to supply heat for vaporization and steam reforming of the fuel. Ambient air is also used to supply oxygen to the cathode and to cool the fuel cell stack. A voltage regulator provides regulated 48 VDC output.

For organizational purposes, the power plant is subdivided into four major subsystems: fuel cell, fuel conditioning, electrical, and power conditioning. The functional interaction between the various subsystems is shown in Figure 2.2.

2.2 OPERATION

The fully automatic power plant has three distinct modes of operation:

1. Standby (start-up)
2. Ready (run)
3. Shutdown

The control components used for operation and control are shown in Figure 2.3. The position of the various components according to operating mode is given in Table 2.1.

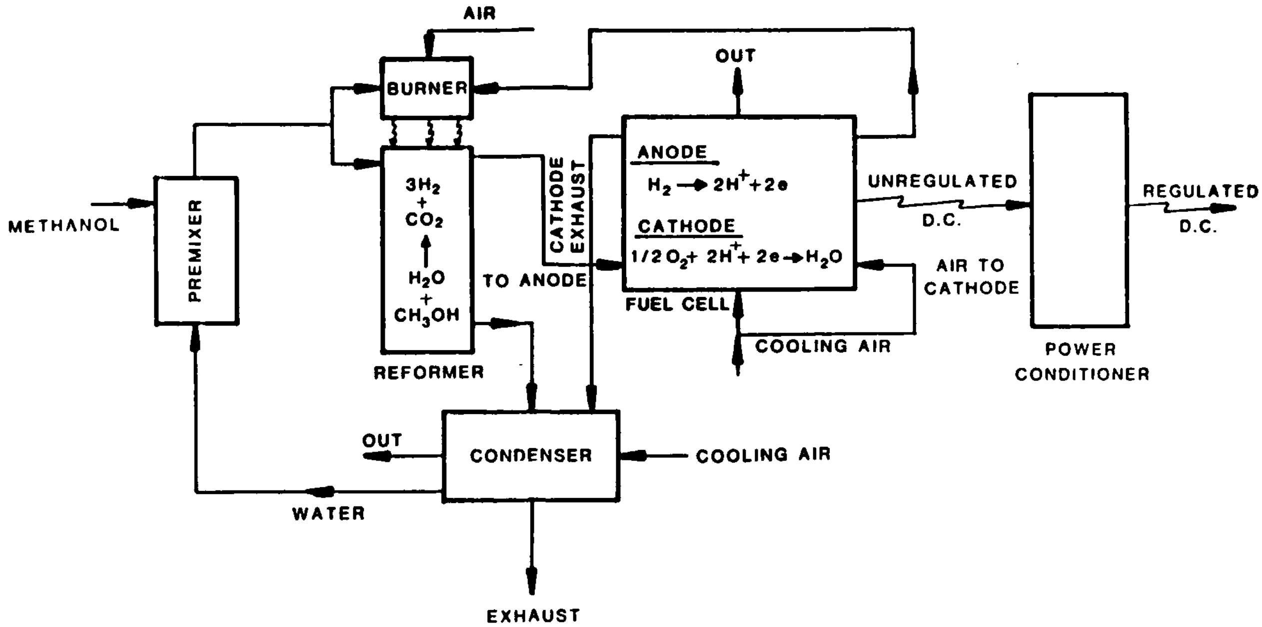


FIGURE 2.1

5 kW FUEL CELL POWER PLANT CONCEPT

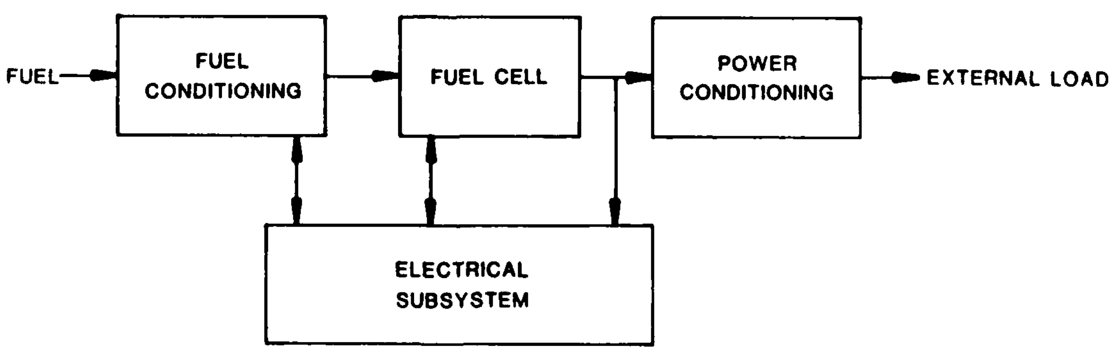


FIGURE 2.2

FUEL CELL POWER UNIT - SUBSYSTEMS BLOCK DIAGRAM

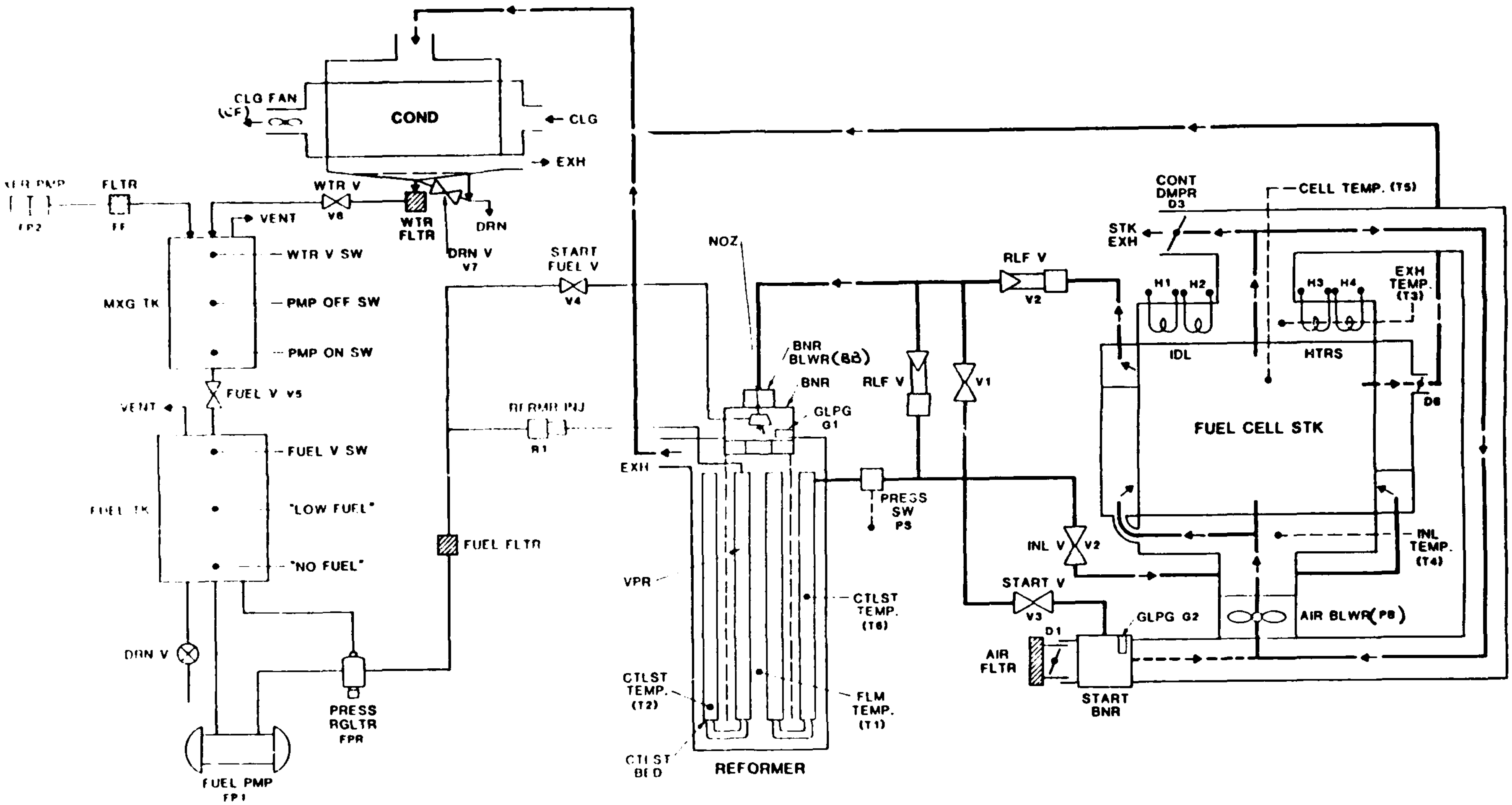


FIGURE 2.3

5kW METHANOL POWER PLANT - FUNCTIONAL SCHEMATIC

TABLE 2.1

METHANOL POWER PLANT CONTROL COMPONENTS

	STANDBY			SHUTDOWN (MANUAL OR SYSTEM)		
	FIRST 4-5 MIN.	SECOND PERIOD	READY (RUN)	FIRST ACTION	SECOND ACTION	EMERGENC[Y] STOP
Start Fuel Valve, V_4	Open	Open	Closed	Closed	Closed	Closed
Transfer Pump, FP2	Controlled	Controlled	Controlled	Controlled	Off	Off
Fuel Pump, FP1	On	On	On	Off	Off	Off
Reformer Injector, RI	Off-Controlled	Controlled	Controlled	Off	Off	Off
Bypass Valve, V1	Open	Closed	Closed	Open	Closed	Closed
Inlet/Return Valve, V2	Closed	Closed	Open	As Is	Closed	Closed
Start Burner Valve, V3	Closed	Open	Closed	As Is	Closed	Closed
Start Burner Damper, D1	Closed	Open	Open	Open	Closed	Closed
Control Damper, D3	Closed	Open	Variable	As Is	Closed	As Is
Exhuast Damper, D6	Closed	Closed	Open	Open	Closed	Closed
Burner Blower, BB	Controlled	Controlled	Controlled	Full Speed	Off	Off
Air Blower, PB	Off	On	On	As Is	Off	Off
Idling Heaters, (H1, H2 & H3)	Off	Off	Controlled	Off	Off	Off
Output Relay, K1	Off	Off	On	Off	Off	Off
Battery Relay, K2	On	On	Off	On	Off	Off
Parasitic Relay, K3	Off	Off	On	Off	Off	Off
Condenser Fan, CF	Off	Off	On	On	Off	Off

Figure 2.4 shows the main control panel. Startup of the power plant is initiated by moving the START/OFF switch to the START position. The STANDBY indicator lamp on the panel lights up. Liquid fuel is combusted in the reformer burner and reformer product gas is combusted in the start burner. The start burner product gas is used to heat the fuel cell stack. When the reformer and stack reach operating temperature, the liquid fuel flow to the reformer burner is shut off and the burner operates on tailgas returning from the fuel cell. After completion of startup, the READY lamp comes on indicating that the power plant is ready to supply power.

Shutoff of the power plant is accomplished by moving the START/OFF switch to the OFF position. At the end of the shutdown mode, all valves and dampers are closed, and all electrical components are disconnected.

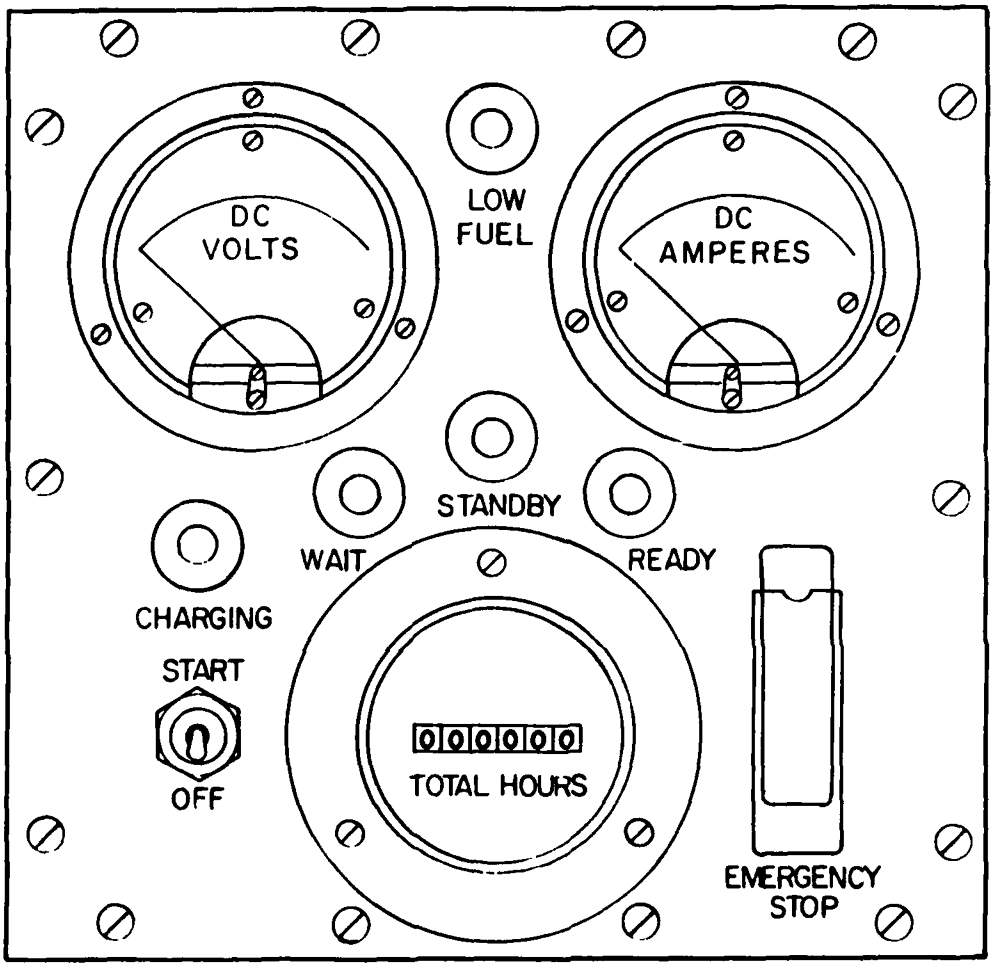


FIGURE 2.4

POWER PLANT MAIN CONTROL PANEL

3.0 SUBSYSTEM DESIGN

3.1 FUEL CELL

The fuel cell subsystem comprises the fuel cell stack, air blower, and air valves. The stack has separate flow paths for fuel, process air, and cooling air. The gases are distributed to the 100 cells by means of shallow pan manifolds as shown in Figure 3.1.

Table 3.1 lists the design and operating parameters for the fuel cell subsystem. Sizing of the 5 kW stack was based on the 6.0 kW gross power requirement while operating at the minimum cell performance of 0.667 volt with a stack load of 90 amperes. An available cell size of approximately 162 in^2 of active area requiring 100 cells to meet the power output goal was selected.

A photograph of the 100-cell stack without the manifolds is shown in Figure 3.2. The overall cell dimensions are 12 in. x 17 in. Channels are included on each plate for acid replenishment. Cooling air channels are used in every fifth plate.

The control damper regulates incoming air rates by controlling the rate of hot air exhaust in accordance with the exhaust air temperature sensor output. Three resistance heaters located in the stack cooling air loop are switched across the stack terminals at low output loads to maintain stack current and temperature. With progressively increasing load, the heaters are sequentially disconnected.

3.2 FUEL CONDITIONER

A functional schematic of the fuel conditioner subsystem is shown in Figure 3.3. This subsystem is comprised of a water recovery and metering system, a liquid fuel delivery system, a reformer assembly, and a startup burner.

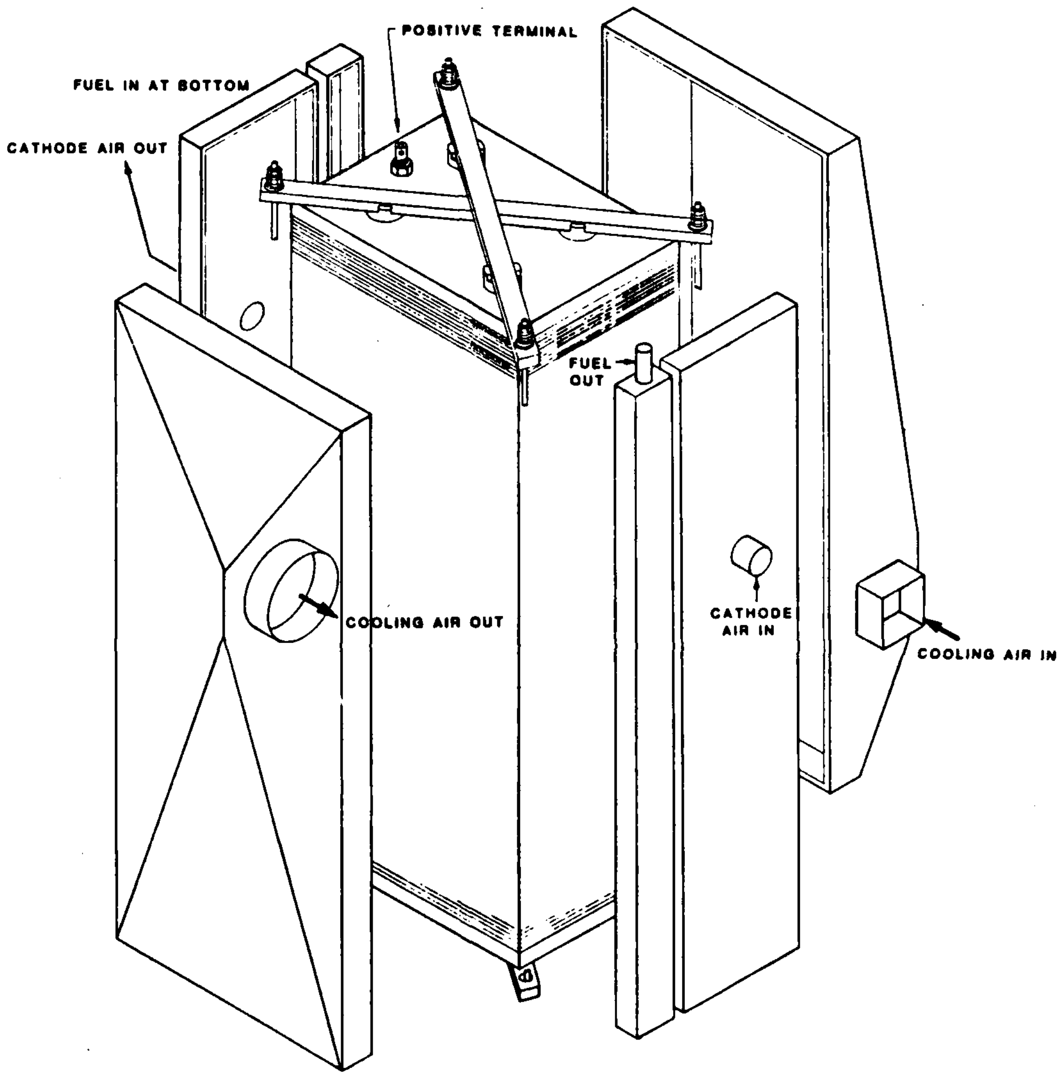


FIGURE 3.1

ASSEMBLY SKETCH OF THE FUEL CELL FOR THE 5 kW AIR FORCE POWER PLANT

TABLE 3.1

FUEL CELL SUBSYSTEM DESIGN

FUEL CELL STACK	
Power Output, kW	6.0
Operating voltage, volts	66.7
Operating current, amperes	90
Hydrogen consumption, lbs/hr	0.74
Hydrogen utilization, %	65
Number of cells	100
Number of cooling plates	19
Cell dimensions, in.	11.5 x 16.3
Active area, in^2/cell	162
Design cooling air ΔT, ^oF	50
Design air side ΔP, in. H_2O	1.0
AIR BLOWER	
Air flow rate, cfm at 250^oF	300
Design ΔP, in. H_2O	1.6
HEATERS	
Power rating, watts	3 x 1000

FIGURE 3.2
PHOTOGRAPH OF STACK WITHOUT MANIFOLDS

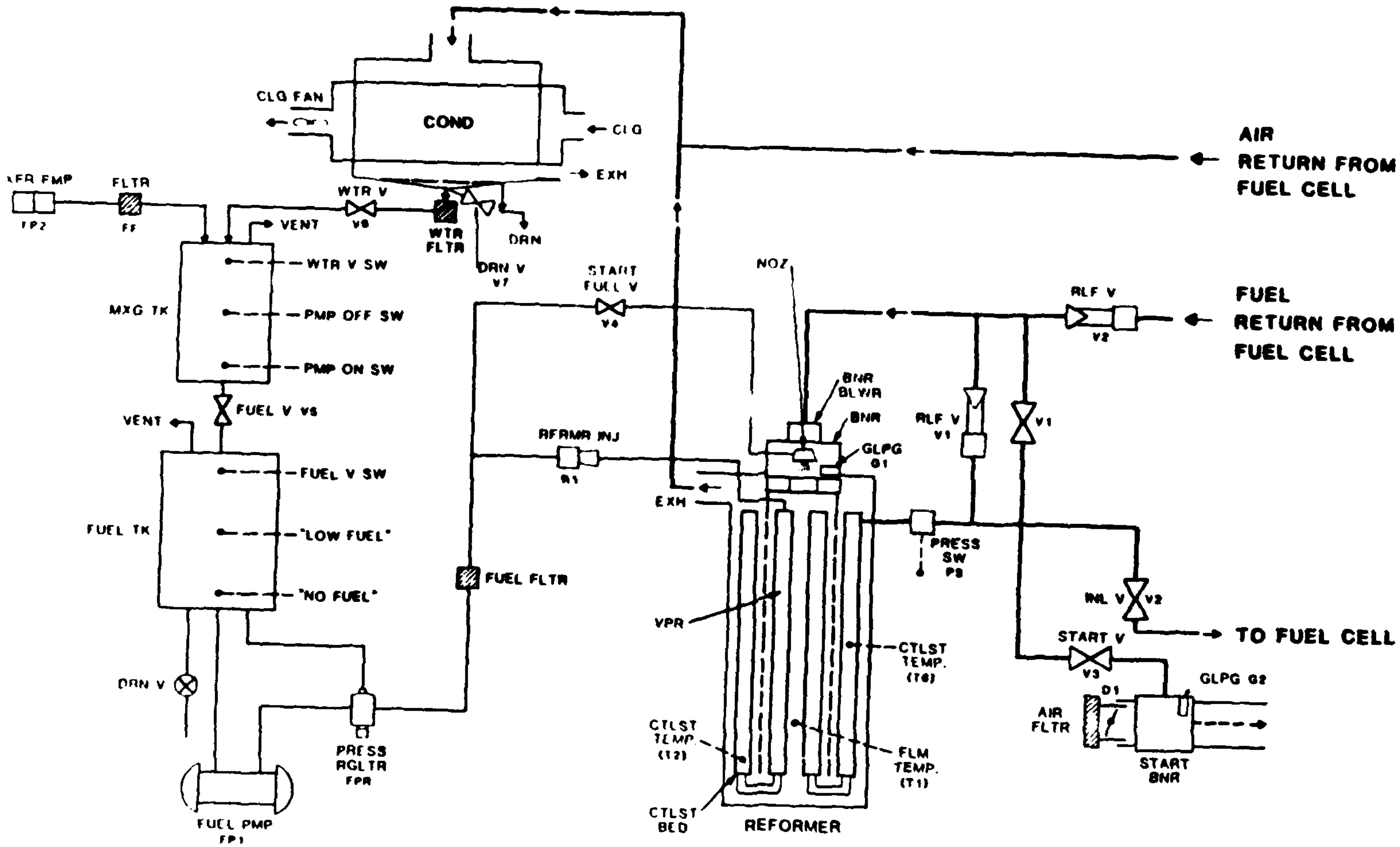


FIGURE 3.3

SCHEMATIC OF THE FUEL CONDITIONING SUBSYSTEM

3.2.1 Water Recovery System

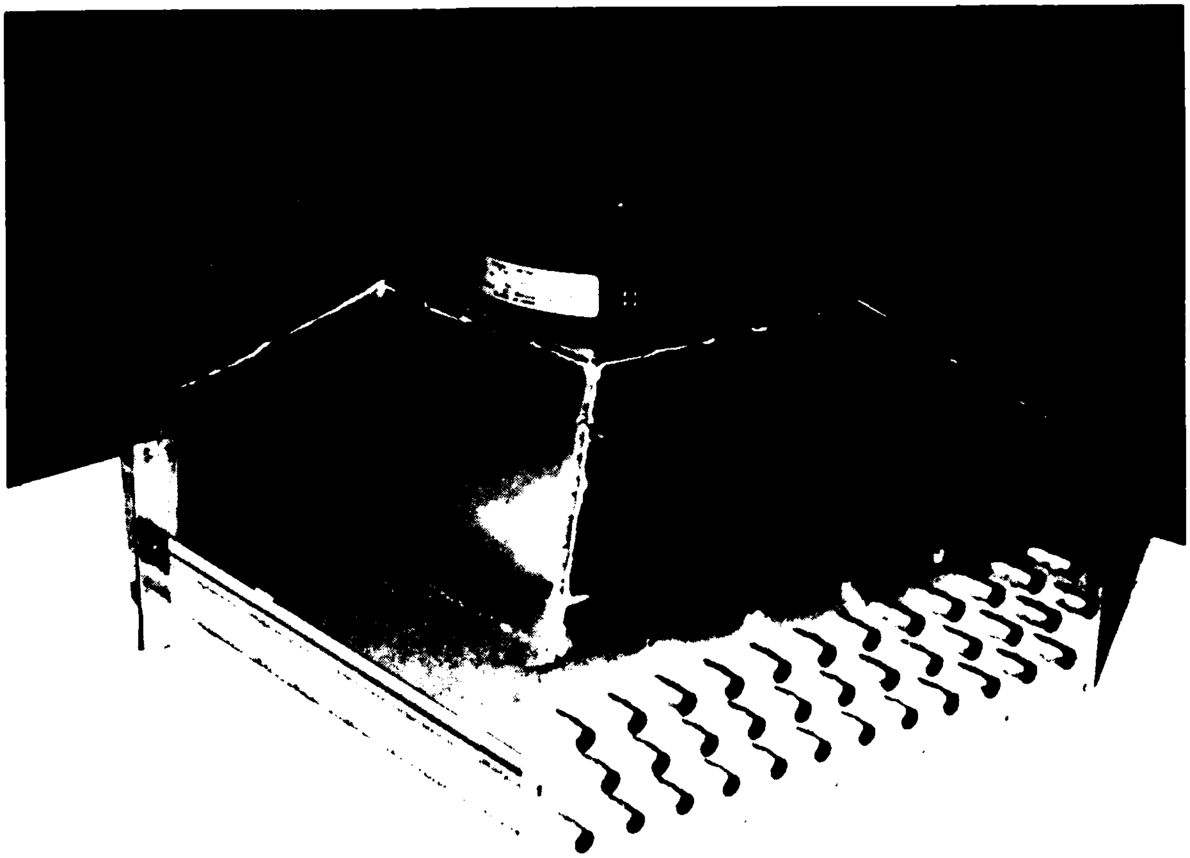
The power plant design incorporates recovery of water from the power plant exhaust streams for use in the steam reformer. The stack cathode exhaust gas and reformer flue gas streams of a fuel cell power plant operating on a 1:1.3 molar mixture of methanol-water fuel together carry 3.3 moles of water for each mole of methanol consumed. To meet the reformer water requirement, 39% of this water is recovered.

The water recovery system for the 5 kW power plant is shown in Figure 3.3. Water is recovered from the stack cathode and reformer flue streams by the use of the air-cooled condenser shown in Figure 3.4. The recovered water is mixed with methanol in a small mixing tank. To obtain the desired methanol-water ratio, methanol is first brought to a preset level in the mixing tank. Next, water from the condenser flows into the tank to a second predetermined level. The mixing tank is then emptied into the premixed fuel holding tank. The system cycles continuously and is controlled automatically by float switches and magnetic relays.

3.2.2 Fuel Delivery System

The internal premixed fuel reservoir holds a 150 minute fuel supply at 5 kW output. If the external fuel supply runs dry or sufficient water is not reclaimed by the condenser while the system is operating, the continuing drop in reservoir level actuates the "Low Fuel" warning light switch to indicate that the internal fuel level is down. Additional drop in fuel level actuates the "No Fuel" switch to automatically shut down the power unit.

The main fuel pump (FP1) maintains a constant flow of fuel to the pressure regulator (FPR) which provides constant fuel pressure to the start fuel valve (V4) and the reformer injector



CONDENSER SPECIFICATIONS:

Manufacturer:	Sundstrand Heat Transfer Inc.
Dimensions, in.:	15 x 15 x 5.25
Tube Diameter, in.:	0.5
Tube Material:	Copper
Cooling Fan:	Saucer Fan, 300 CFM @ 0.07 in H_2O

FIGURE 3.4

THE CROSS-FLOW AIR-COOLED CONDENSER IS USED FOR WATER RECLAMATION

(RI). The start fuel valve is open during startup to deliver liquid fuel to the reformer burner nozzle. The reformer injector is modulated in response to stack current and reformer temperature sensor outputs.

3.2.3 Reformer

The function of the reformer assembly is to convert liquid fuel into a gas mixture containing free hydrogen for use in the fuel cell stack. The reformer comprises a catalyst bed, a vaporizer/superheater, a burner, and a burner air fan. A cross-sectional sketch of the reformer assembly is shown in Figure 3.5.

The upflow bed design is based on a maximum product gas space velocity of 2700 hr^{-1}, corresponding to a premixed fuel processing rate of 11.2 lb/hr. A commercial zinc-copper catalyst is used in the bed. The reformer catalyst temperature ranges between 450 and 650^{o}F depending upon fuel feed rate. Typical gas composition under these operating conditions is 74% H_2, 24.5% CO_2 and 1.5% CO on a dry basis.

A fast response vaporizer/superheater generates superheated vapor from the liquid fuel input. The gaseous fuel is superheated to approximately 900^{o}F. A burner flame temperature sensor and two reformer bed temperature sensors provide input to the control subsystem.

The burner is designed to burn both liquid fuel during startup and gaseous fuel from the stack anode exhaust during the run mode. A platinized honeycomb disk below the combustion chamber aids complete combustion of the fuel. A variable speed air fan provides combustion air flow.

The flow of reformate from the catalyst bed is switched by three solenoid valves and a pressure actuated check valve. A

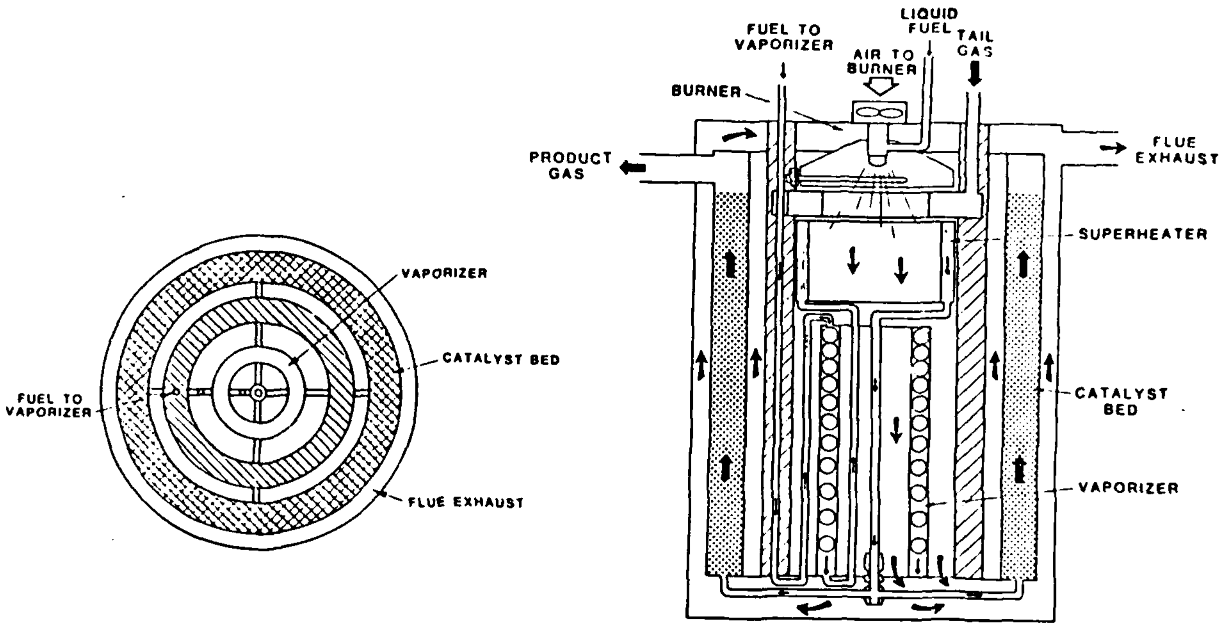


FIGURE 3.5
CROSS-SECTIONAL SKETCH OF THE REFORMER ASSEMBLY

pressure sensor triggers an emergency shut-down of the power plant if the line pressure exceeds 2 psi.

A photograph of the fully assembled 5 kW reformer is shown in Figure 3.6.

3.2.4 Startup Burner

The startup burner shown in Figure 3.7 is used for stack warmup heat generation. Air enters through an annular space between the combustion chamber and the cover cylinder and travels the length of the combustion chamber before entering through the air sealing damper. This arrangement preheats the combustion air and reduces the combustion chamber skin temperature. The air mixes with the gaseous fuel and is ignited by the glow plug. A

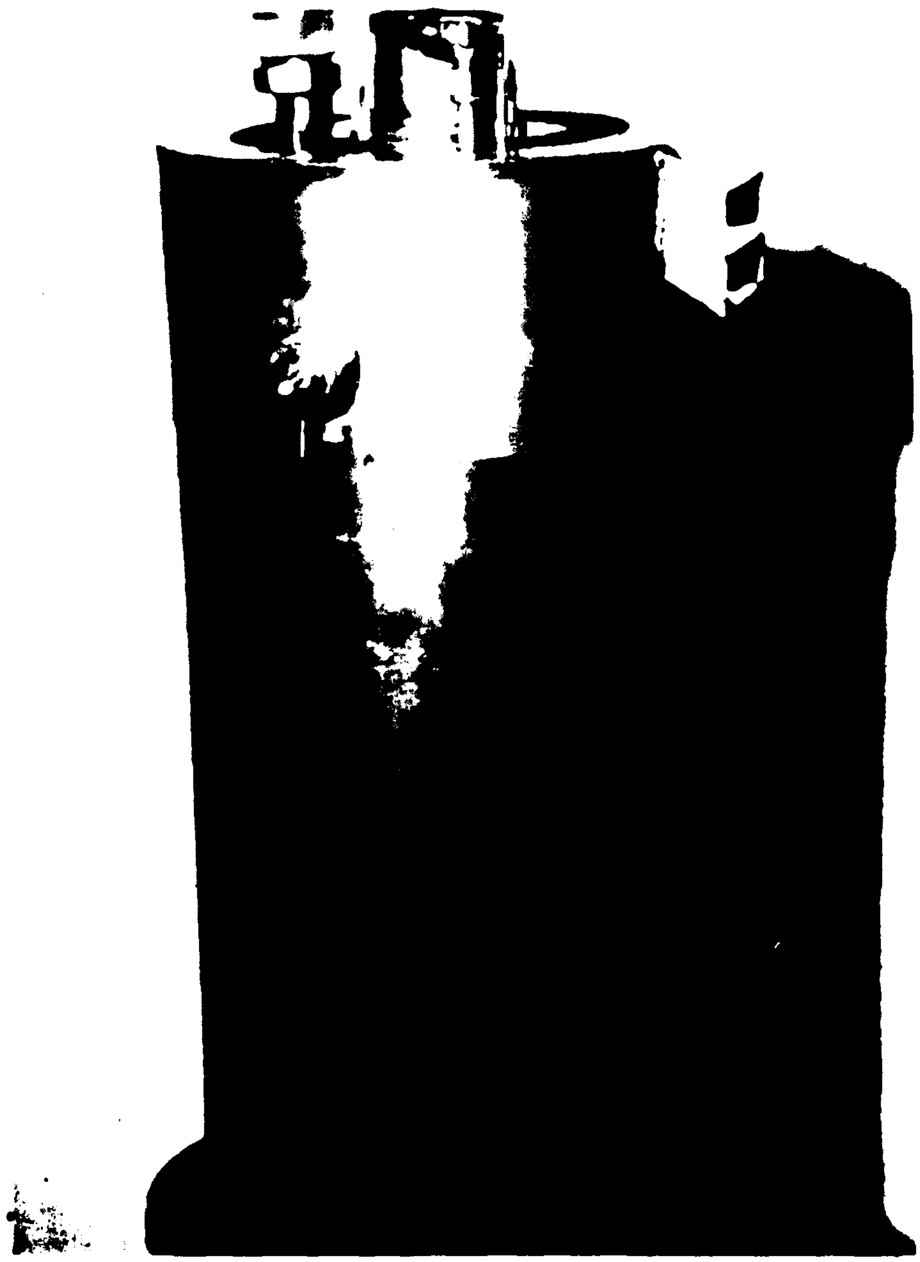


FIGURE 3.6
A PHOTOGRAPH OF THE 5 kW REFORMER

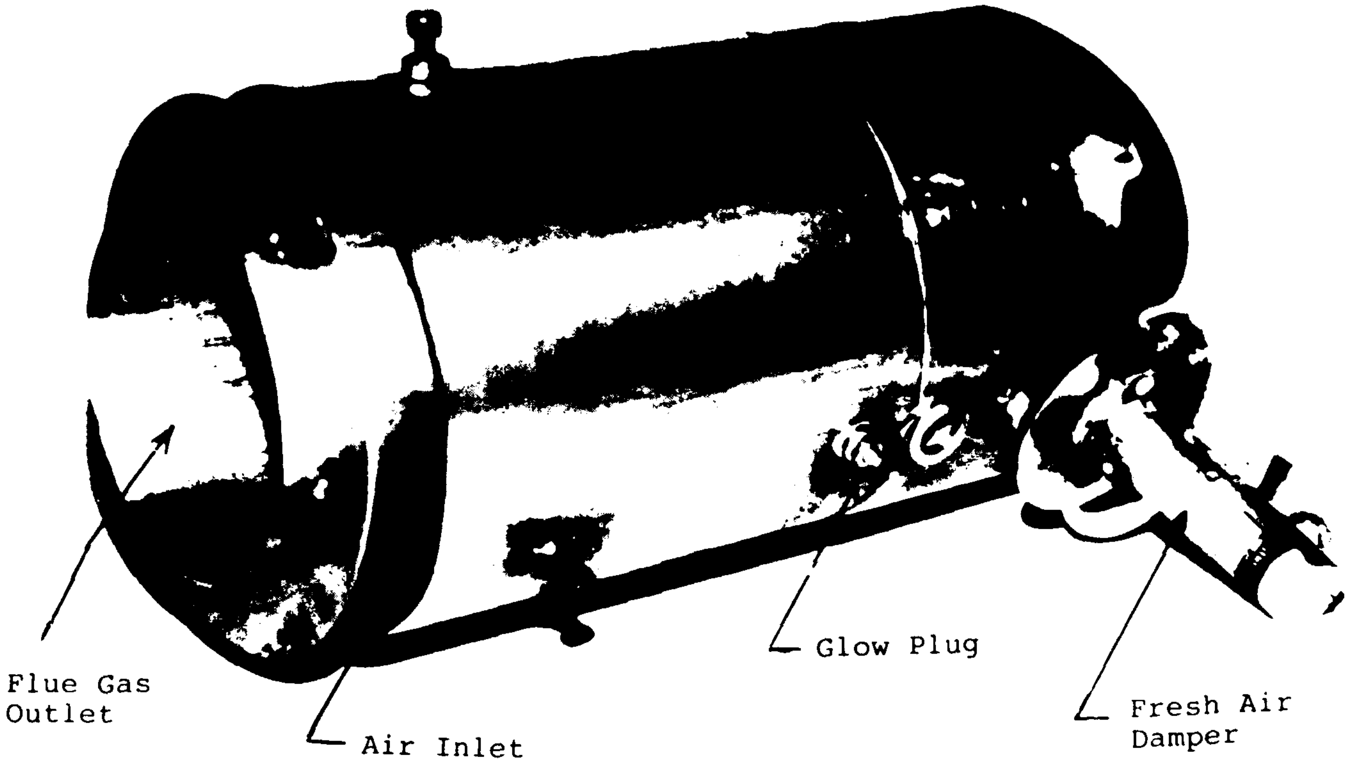


FIGURE 3.7

A PHOTOGRAPH OF THE STARTUP BURNER

deflector ring located immediately downstream of the ignitor aids mixing of the air and fuel during combustion.

3.3 ELECTRICAL SYSTEM

This subsystem includes all ancillary components required for powering and controlling the electrically driven elements of the power plant. A functional block diagram of the electrical system is shown in Figure 3.8.

3.3.1 Starting Battery and Charger

Starting power is supplied by an internal 24 V, 20 Ah sealed lead-acid battery which is recharged by an internal charger after the system has completed its startup cycle. Startup requires about 12 Ah of capacity from the battery during a 40 minute room temperature start.

The battery charger provides a constant current source at nominally 1 A for charging and 20 mA for full charge float. An indicator light on the main control panel remains on while the battery is being charged. When the battery reaches full charge, the charger switches to float automatically and the indicator light goes off.

3.3.2 Housekeeping Power Supply

The housekeeping power supply provides the regulated DC power necessary to operate the power plant controls. The voltages used to power the controller loads are the following:

1. $\pm$24 VDC: fuel cell stack blower inverter, solenoids, motors, relays and pumps.
2. 5 VDC: fuel injector.
3. 5 VDC, $\pm$15 VDC: microprocessor control system.

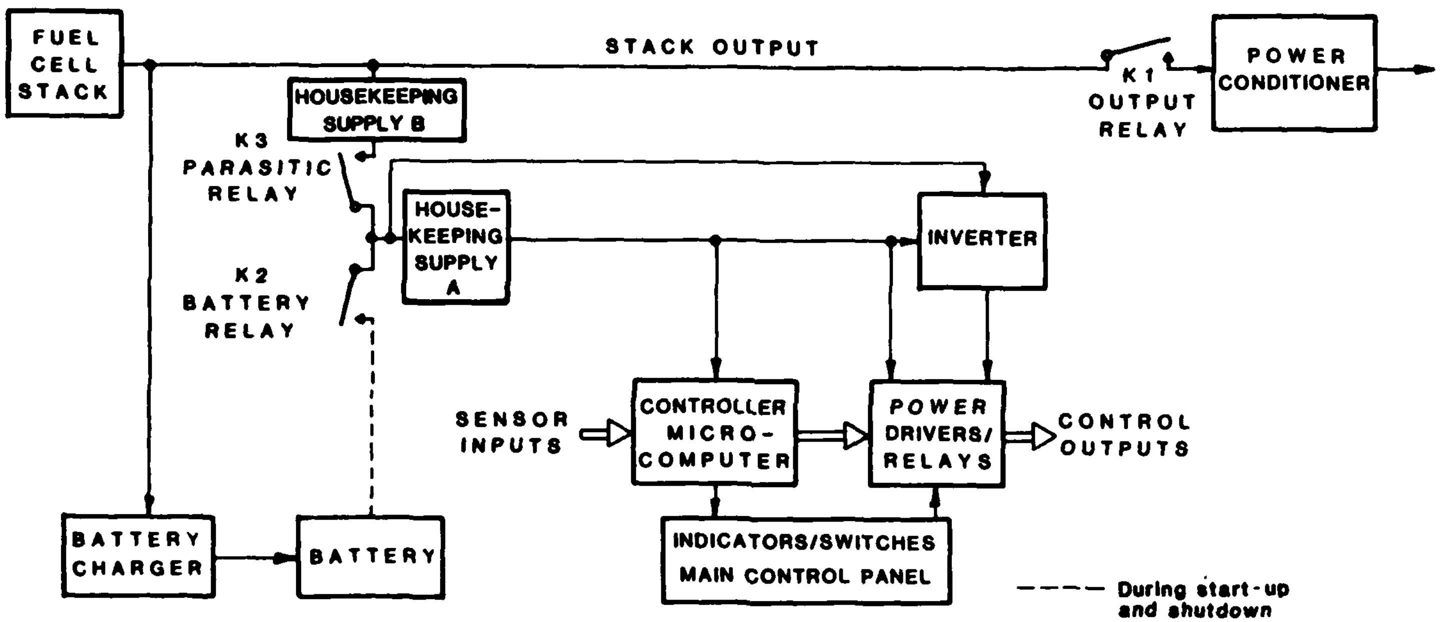


FIGURE 3.8

ELECTRICAL SYSTEM - BLOCK DIAGRAM

The housekeeping power supply consists of two independent power supplies (Unit A and Unit B) in a common enclosure. The Unit B supply provides the 24 VDC bus voltage of the system. The Unit A supply is powered by the 24 V bus and provides isolated power of +5 VDC and $\pm$15 VDC for the microprocessor. It also provides +5 VDC to power the injector and -24 VDC for the power drivers. This DC to DC converter operates either from the regulated 24 VDC bus or from the internal battery.

A separate 400 Hz, 115 VAC inverter powers the stack air blower and the condenser fan. This inverter is also powered by the 24 V bus.

3.3.3 Connectors

An Auxilliary Startup Power Connector located on the lower left of the power plant front panel is used for connecting an external battery or other 24 VDC power source in case of low output from the internal battery. The connector accepts the mating plug on a standard NATO tank cable. A ground connector available at the lower right at the left hand-side of the power plant provides connection for an electrical earth ground to the frame of the power plant.

3.3.4 Controller

The controller consists of a microcomputer, a power driver assembly, a relay assembly, and a main control panel containing manual controls and indicators. All of the control subsystem components are powered from the housekeeping power-supply. Input to the microcomputer include temperature readings from temperature sensors located in the reformer and fuel cell stack assemblies, and voltage and current measurements of fuel cell output. The microcomputer provides output to the main control panel indicators and the power driver/relay circuits which control system operation.

A. Microcomputer

The controller microcomputer assembly contains four printed boards (an analog module, a CPU module and two isolator modules for input and output signals). This microcomputer was designed, assembled and programmed by Consolidated Controls Corporation (Danbury, CT) using an Intel 8031 series CPU module having 4 K bytes of memory. The program is written in machine language and stored in the UVEPROM.

B. Control Panel

The main control panel is pictured in Figure 3.9. It contains switches, meters, and indicators, and provides the operator with the means for starting, stopping and monitoring the operation of the power plant. A description of the power plant control panel functions is given in Table 3.2.

C. Power Drivers

The power drivers are contained in three separate boxes. One box, designed and built by Consolidated Controls Corporation (Danbury, CT), contains all driver circuits that handle the control of power to the ancillary components. The other boxes were built by ERC and contain relays and automatic water recovery-fuel premixing system electronics. The power driver circuits are controlled by the microprocessor by means of the opto-isolated digital interface and are physically isolated from the microprocessor to enhance noise and heat rejection.

The relay assembly box contains the relays for switching the solenoids, motors, and pumps. These relays are controlled from the power driver switching circuits. Two 10 amp fuses which are used to fuse the two glow plugs or ignitors are included in the relay assembly.

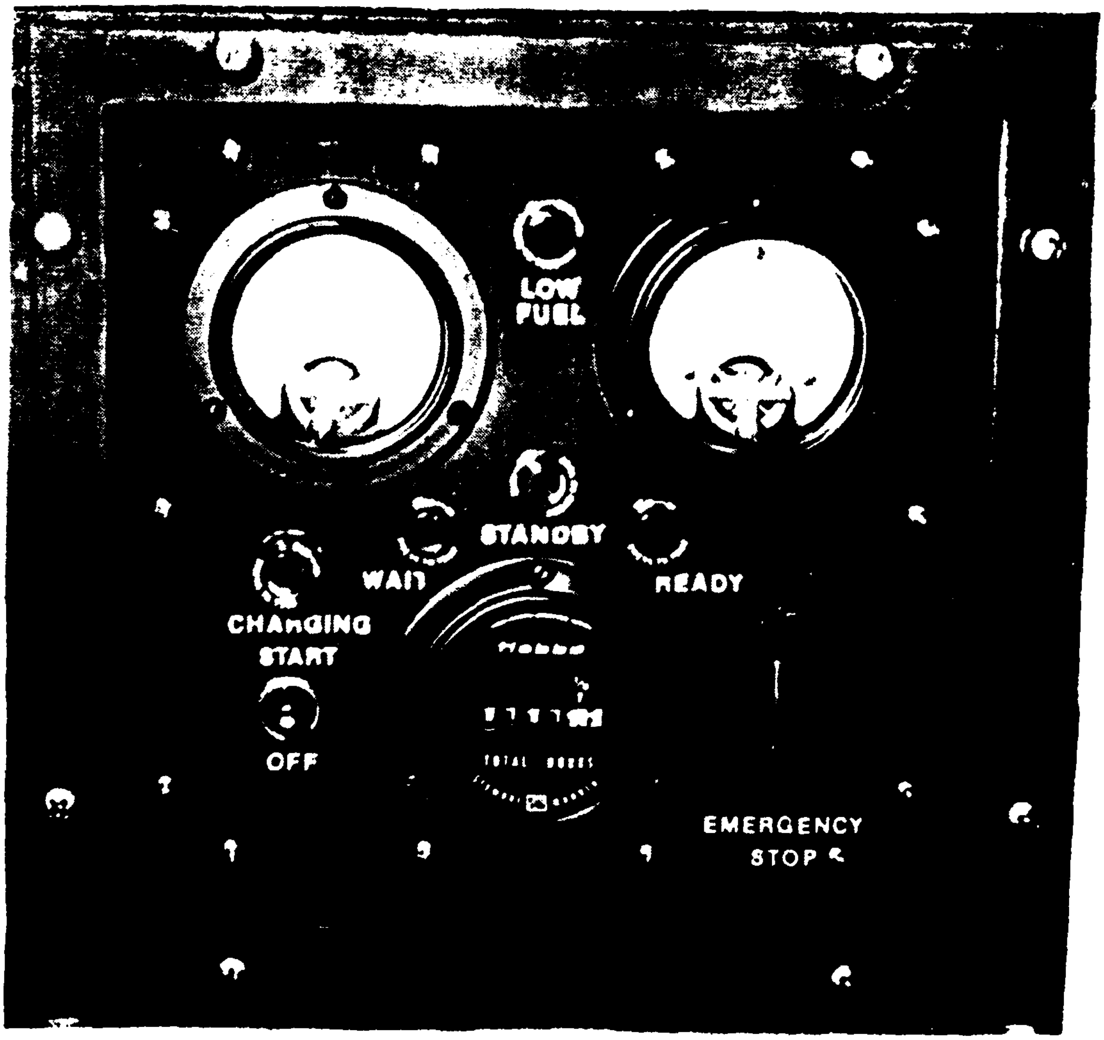


FIGURE 3.9
A PHOTOGRAPH OF THE POWER PLANT CONTROL PANEL

TABLE 3.2

MAIN CONTROL PANEL - CONTROLS AND INDICATORS

CONTROL/INDICATOR	DESCRIPTION
START/OFF	Three position switch with spring return to center position. START initiates startup. OFF initiates shutdown.
EMERGENCY STOP	Guarded switch, normally OFF, must lift guard to move to STOP position. Used for emergency shutdown only.
LOW FUEL	Panel light, push-to-test, twist-to-dim. Lit when fuel in the internal reservoir is below 8 minutes of full load operation.
CHARGING	Panel light, push-to-test, twist-to-dim. Lit when battery is charging.
WAIT	Panel light, push-to-test, twist-to-dim. Lit during shutdown, must be off to restart.
STANDBY	Panel light, push-to-test, twist-to-dim. Lit during startup before unit is ready to supply power.
READY	Panel light, push-to-test, twist-to-dim. Lit when unit is ready to supply power.
DC VOLTS	0-75 VDC Voltmeter. Indicates fuel cell voltage.
DC AMPERES	0-150 ADC Ammeter. Indicates fuel cell current using 50 mV/150A SHUNT.
TOTAL HOURS	0-9999 digital meter. Displays total operating time of unit.

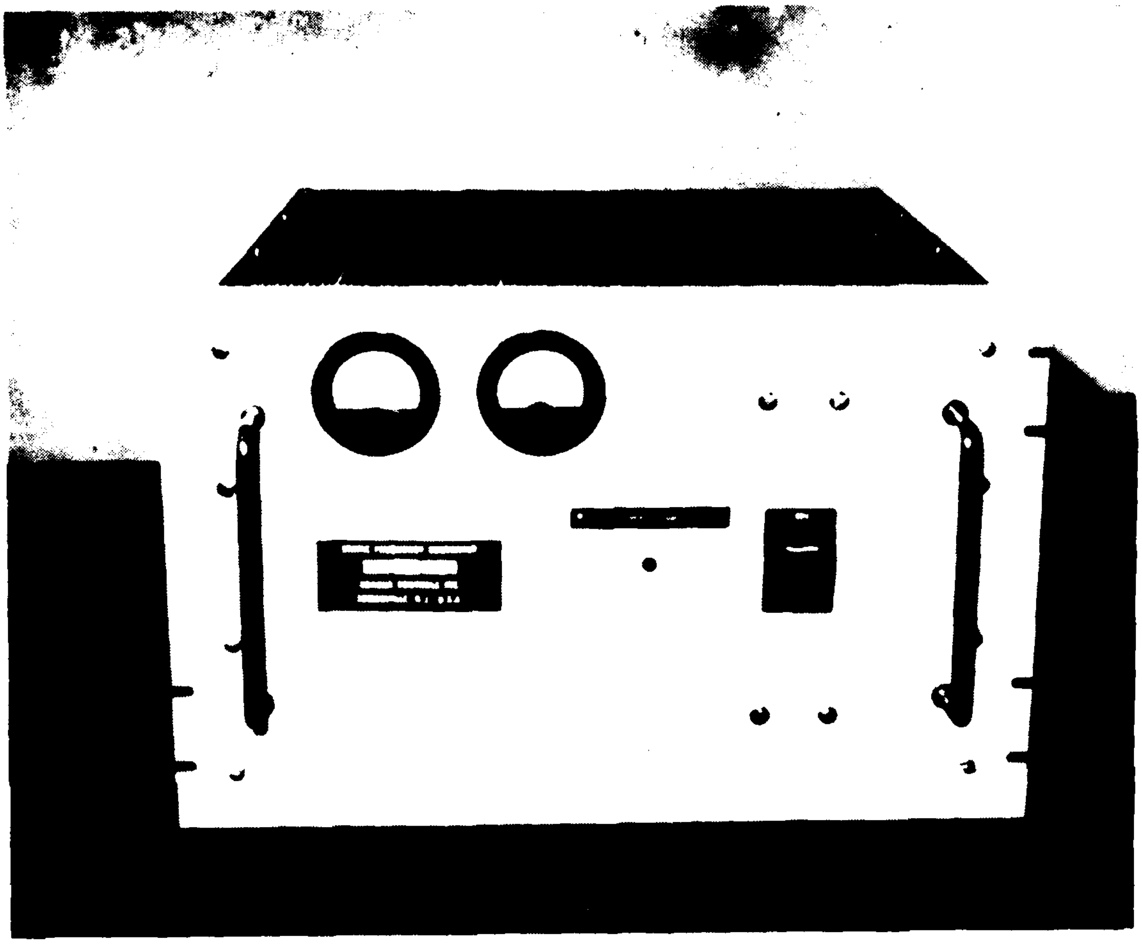
The automatic water recovery assembly is not microprocessor controlled. It operates on float switches and magnetic relays which hold the output even when the power unit is powered down. Reset switches located in the unit are used to reset all relays if the fuel mixing sequence has been manually interrupted.

3.4 OUTPUT VOLTAGE REGULATOR

The power plant includes a DC-DC output voltage regulator to provide regulated 48 VDC output. The regulator was supplied by Abacus Controls Corporation (Somerville NJ).

The front panel of the regulator provides for an on/off switch and meters for monitoring the output load. The regulator is internally protected from reverse polarity connection and overload.

A photograph of the regulator unit used for the 5 kW power plant and the specifications provided by the manufacturer are shown in Figure 3.10.



REGULATOR SPECIFICATIONS:

Manufacturer	Abacus Controls Corp.
Input Voltage Range, VDC	60 to 80
Output Voltage, VDC	48
Output Voltage adjustment (internal)	43 - 65 VDC
Output Voltage Regulation	1%
Ripple	1%
Temperature Range	-25°C to +55°C
Dimensions H x W x D, in.	
Weight, lbs	120

FIGURE 3.10
OUTPUT VOLTAGE REGULATOR

4.0 5 kW POWER PLANT PERFORMANCE

The 5 kW DC power plant was evaluated for automatic startup, ability to assume variable load, fuel consumption, auxiliary power consumption, and overall efficiency.

The power unit has been successfully operated with a variable DC load (0-5 kW) on externally supplied Grade OM-232 methanol fuel. The unit completed over 50 successful automatic starts. Room temperature startup required 30-40 minutes and less than 3 minutes if restarted warm immediately after shutdown. Methanol consumption for room temperature startup was ≅4.2 lbs. In addition, ≅270 Whr of electrical output from the onboard 24 V lead acid battery was required for a room temperature start. Three minutes were needed to completely shutdown the power unit.

The power plant was run at 0-5 kW loads for a total of ≅100 hours in the room environment and ≅450 hours in uncontrolled outdoor environment during August-October 1985. A thunderstorm that hit the Danbury, Connecticut area during the outdoor test causing local electrical utility supply failures had no effect on the power plant.

The fuel cell stack characteristics are shown in Figure 4.1. Power plant voltage and power curves are shown in Figure 4.2. About 6.0 kW was developed by the fuel cell stack for a net power plant output of 5 kW DC. The discontinuities in the power curves are due to the three internal stack heaters which disconnect sequentially with increasing load.

The key operating parameters for the 5 kW power plant are listed in Table 4.1. Neat methanol consumption varied from 3.75 lb/hr at idle to 6.28 lb/hr at 5 kW. For the 5 kW DC operation, the overall thermal efficiency was 32% (LHV).

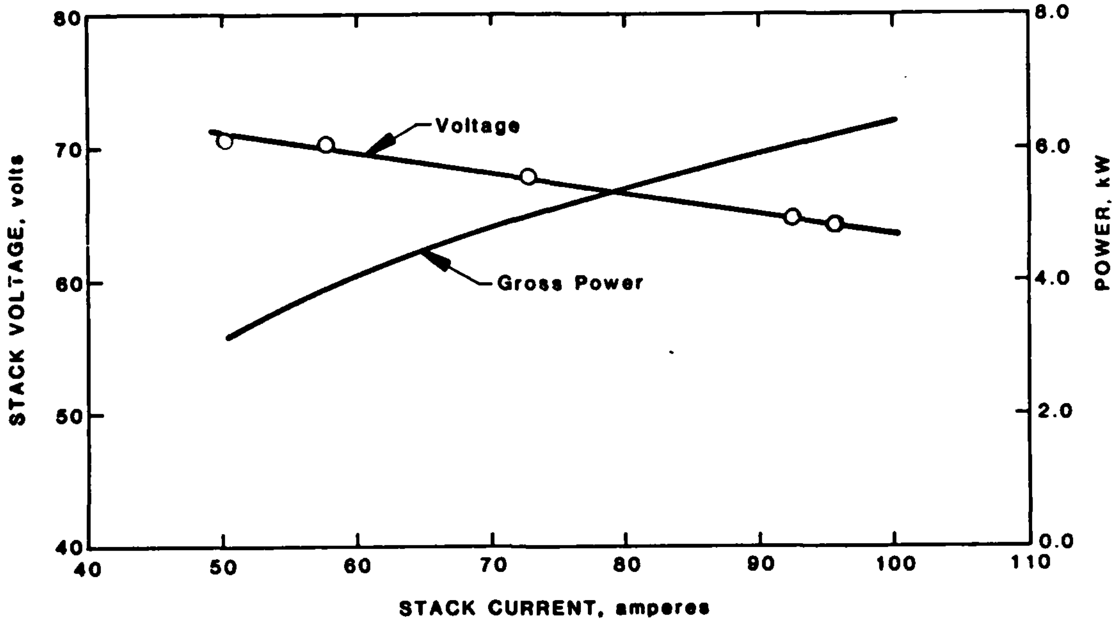


FIGURE 4.1
FUEL CELL STACK PERFORMANCE (REFORMED FUEL)

A summary of internal housekeeping power supply and power conditioning efficiencies are reported in Table 4.2. The housekeeping power supply operated at an efficiency of about 89% and the DC regulator efficiency at full load was 93%. Parasitic power of ~600 watts was drawn from the fuel cell stack by the housekeeping power supply.

Results of the 5 kW power plant testing showed sufficient water reclamation for continuous operation at all loads. Automatic on-board mixing of methanol and reclaimed water (58 wt% CH_3OH and 42% water) was also successfully demonstrated.

The unattended operation period produced some unscheduled automatic shutdowns. As a result, improvements were made in the design of the condenser water filters, stack fuel filter, cathode return duct, and the micro-switch for stack gas valves. This test

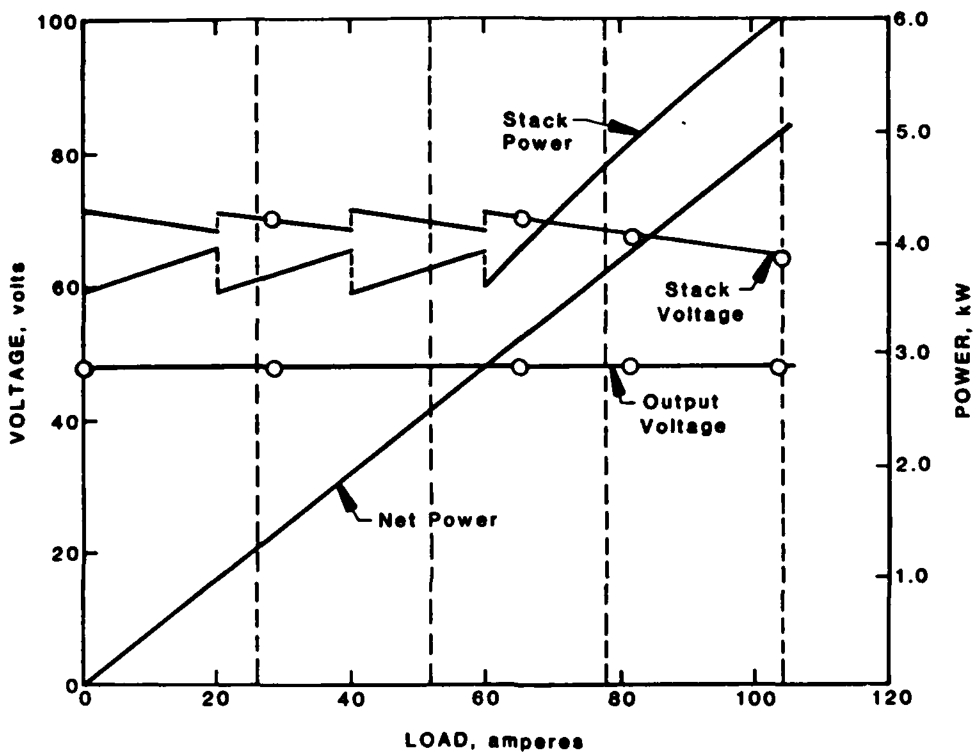


FIGURE 4.2

VOLTAGE POWER CURVES FOR THE 5 kW
FUEL CELL POWER PLANT

TABLE 4.1
POWER PLANT OPERATING PARAMETERS

Regulated Output				
Volts	48	48	48	48
Amperes	-	66	82	104
Watts	-	2500	3930	4990
Stack Output				
Volts	71.2	70.3	67.7	64.8
Amperes	50.3	57.6	72.8	92.6
Watts	3581	4049	4930	6000
Air Out, ^{o}F	354	353	350	356
Air In, ^{o}F	360	335	330	315
Parasitic Load Watts	605	598	596	583
Reformer Temperature, ^{o}F	600	580	510	520
CH_3OH Consumption, lb/hr	3.75	4.30	5.06	6.28
Overall Efficiency, %	-	29	31	32

TABLE 4.2

HOUSEKEEPING SUPPLY AND POWER CONDITIONING EFFICIENCIES

GROSS FUEL CELL POWER kW	EXTERNAL LOAD kW	NEAT METHANOL CONSUMPTION Kg/hr	EFFICIENCY, %		
			HOUSE KEEPING SUPPLY	POWER CONDITIONER	OVERALL THERMAL
3.6	0.0	1.7	89	-	-
4.0	3.2	1.9	88	93	29
4.9	3.9	2.3	88	95	31
6.0	5.0	2.8	89	93	32

period also indicated that the reformer fuel injector requires attention if the power plant is not run for a long period. Use of stainless steel injector parts will eliminate this condition since stainless steel is unaffected by the methanol fuel.

5.0 CONCLUSIONS

This program has resulted in the development of a high efficiency 5 kW phosphoric acid fuel cell power source for continuous power generation at remote sites. The power source has been successfully operated both indoors and outdoors for over 500 hours on neat methanol with a variable load.

Improvement of power plant performance through the use of advanced cooler design and cathode catalyst and reduction of parasitic power consumption by using a brushless DC stack fan will increase the overall thermal efficiency. The power plant design can be significantly simplified by repackaging the electrical system and eliminating several components. Additional power plant endurance tests are needed to identify the components affecting reliability and maintenance requirements. Also, cost reduction through value engineering efforts need to be pursued.

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